Hadronic excitation of the octupole bands in deformed nuclei: Necessity of the isoscalar dipole degree of freedom?

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HADRONIC EXCITATION OF THE OCTUPOLE BANDS IN DEFORMED NUCLEI: NECESSITY OF THE ISOSCALAR DIPOLE DEGREE OF FREEDOM?

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Coupled channel analysis indicates that an octupole vibration coupled to the quadrupole static deformation is sufficient to explain the inelastic excitation by proton scattering of the $K^\pi = 0^-$ octupole band in ^{152}Sm. The isoscalar dipole degree of freedom is found not to be necessary, at least for this mass region, to explain the excitation of the 1^- state of the octupole band.

It is quite reasonable to expect [1] that isoscalar dipole excitations defined with respect to the operator $P^{(1)} = \Sigma_i \frac{1}{2} r_i^3 Y_0^1(\Omega_i)$ can assume collectivities similar to octupole excitations defined with respect to the operator $P^{(3)} = \Sigma_i r_i^3 Y_0^3(\Omega_i)$. Isoscalar dipole states at low excitation energies in several nuclei have been observed, similar to low-lying collective octupole excitations, to be strongly populated in inelastic electron [2] and hadron [3] scattering. Recently, also evidence for the excitation of the high energy component ($3\hbar\omega$) of the isoscalar giant dipole resonance was obtained from inelastic hadron scattering [4]. In deformed nuclei, however, the excitation of low-lying negative parity bands has been interpreted [5] as completely due to coupling of octupole vibrations to the static axially symmetric deformed ground state. The excitation of the 1^- and 5^- members of the $K^\pi = 0^-$ octupole band in ^{238}U by inelastic electron scattering was, for example, well explained [6] in this picture with the same octupole phonon amplitude used in fitting the 3^- member of this band and the static deformation parameters obtained from fitting the transitions observed in the ground-state band (gsb).

It has recently been conjectured [7], however, that low-lying negative parity $K^\pi = 0^-$ bands in Ra isotopes and also possibly in Sm and Gd isotopes may arise from α-cluster states which may be represented by excited s* and p* bosons. Since the p-boson results from an isoscalar excitation, a possible way to investigate the nature of these low-lying $K^\pi = 0^-$ bands would be inelastic electron or hadron scattering to investigate whether the 1^- states do in fact result from coupling of a genuine isoscalar dipole excitation or an octupole vibration to the statically deformed ground state. In this letter, we report data on inelastic proton excitation of the $K^\pi = 0^-$ octupole band in ^{152}Sm, the coupled channel (CC) analysis of which show that the excitation of the 1^- member of this band can be explained by assuming the octupole vibration degree of freedom alone and that invoking the presence of an isoscalar dipole degree of freedom is not necessary to explain the data. Similar conclusions have been drawn [8] from the analysis of data for ^{156}Gd but will not be presented here.

The data reported here are part of the data obtained in a study of 50 MeV protons from ^{150}Nd and ^{152}Sm. The analyzed proton beam was obtained from the KVI cyclotron and the elastically and inelastically scattered protons were detected with the QMG/2 magnetic spectrograph [9] and its position sensitive detection system [10] with an overall energy resolution of 25–30 keV. A complete account of this experiment will be published elsewhere [11]. The 1^-, 3^- and 5^- states of the $K^\pi = 0^-$ band in ^{152}Sm at 0.963 MeV, 1.042 MeV and 1.222 MeV, respectively, were completely resolved from nearby lying states. This was not the case for the $K^\pi = 0^-$ band in ^{150}Nd. Angular distributions were measured for angles ranging from $\theta_{\text{lab}} = 15°$ to $87°$. At

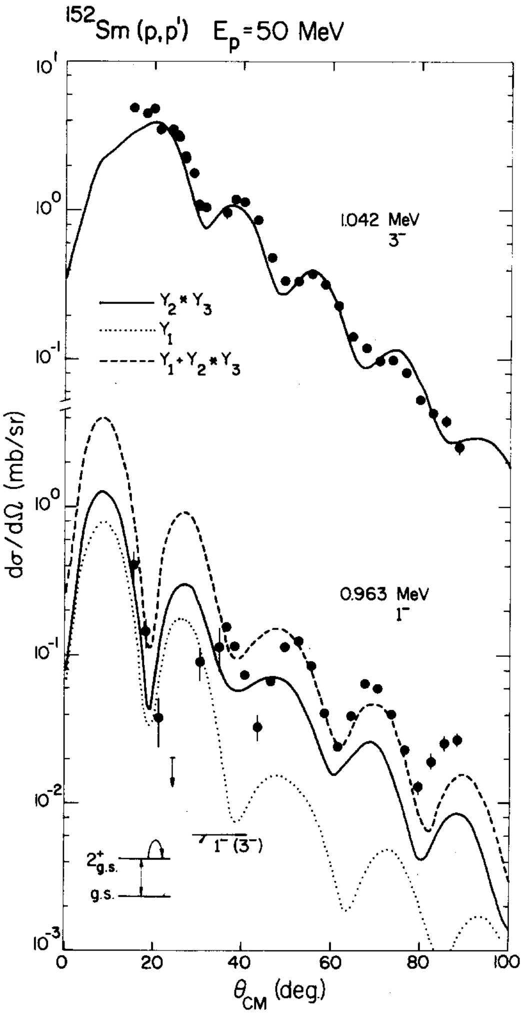

Fig. 1. Experimental and theoretical (DWBA) angular distributions for the 1⁻ and 3⁻ states of the $K^\pi = 0^-$ band in ^{152}Sm. See text for meaning of curves.

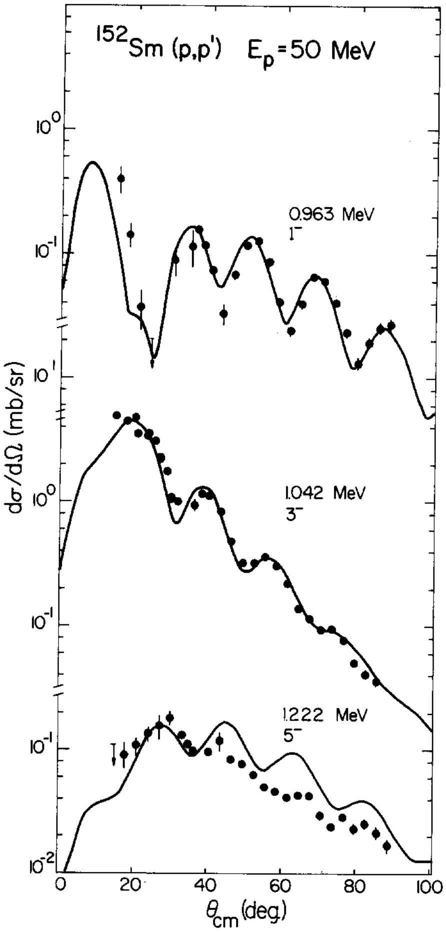

Fig. 2. Experimental differential cross sections for the 1⁻, 3⁻ and 5⁻ states of the $K^\pi = 0^-$ octupole band in ^{152}Sm. Curves are results of a CC calculation as described in the text.

some of the most forward angles, peaks due to light contaminants interferred with the analysis of our data. Moreover for angles between $\theta_{lab} = 15^\circ - 30^\circ$ long runs with good statistics had to be taken to establish the angular distribution of the 1^- state which is crucial for our theoretical analysis and the conclusion we draw as we will discuss shortly. In figs. 1 and 2, differential cross sections for the 1^-, 3^- and 5^- states in ^{152}Sm are shown. Absolute errors in the cross sections are estimated to be less than 10% due to normalization of the elastic cross section to optical model calculations. Relative errors are much smaller.

The form factors used for the following DWBA and CC analyses were obtained along similar lines as those of ref. [6], assuming a small amplitude axially symmetric octupole vibration in the nuclear radius, which leads to form factors for the excitation of the $K^\pi = 0^-$ octupole band (here the optical potential U is assumed to be deformed in the same way as the density):

$$f_{\lambda 0 \lambda} = [(-1)^\lambda/\hat{\lambda}]\,\langle I_\beta 0 \lambda 0 | I_g 0\rangle\,(1/4\pi)^{1/2} \times \sum_l f v_l^{(1)} (\beta_3 \sqrt{7} \langle l0\,30|\lambda 0\rangle^2 - \xi\sqrt{3}\langle l0\,10|\lambda 0\rangle^2)\,, \tag{1}$$

see further ref. [12] for notations used here. The second term within the brackets is to correct for the center of mass spurious motion introduced by the octupole vibration and in that sense ξ is completely determined once β_3 is, by the condition $\int r^3 f_{101}(r)\,\mathrm{d}r \equiv 0$. Therefore there is only one free parameter for the excitation of the octupole band. Form factors for excitation within the same band were taken [12] to be of the usual rotational model type. To take care of a possible extra direct isoscalar excitation for the 1^- state of the band, a form factor of the type [1]:

$$f_{101}(r) = -(\beta_1/R\sqrt{3})$$

$$\times\,(3r^2\,\mathrm{d}/\mathrm{d}r + 10r - \tfrac{5}{3}\langle r\rangle^2\,\mathrm{d}/\mathrm{d}r)\,U(r), \qquad (2)$$

was taken which is already corrected for the spurious center of mass motion. All DWBA and CC calculations were performed using the program CHUCK [13] [‡1].

First we report on DWBA calculations performed for the excitation of the 1^- and 3^- states. In these calculations optical model parameters (OMP) were used as obtained from a χ^2-fit to the data of the gsb ($0^+, 2^+$, 4^+ and 6^+ members) in a CC scheme using program ECIS [14]. To take into account the removal of flux the entrance channel due to the strong coupling between gs and 2_g^+ state, this coupling was specifically included in these DWBA calculations (see fig. 3 for the coupling scheme). The OMP and the deformation parameters of the gsb are, in usual notation: $V = -49.2$ MeV, $r_R = 1.165$ fm, $a_R = 0.824$ fm, $W = -10.5$ MeV, $r_I = 1.364$ fm, $a_I = 0.715$ fm, $V_{so} = 5.61$ MeV, $r_{so} = 1.075$ fm, $a_{so} = 0.816$ fm, $r_c = 1.25$ fm, $\beta_2 = 0.246$ and $\beta_4 = 0.066$.

‡1 The program was slightly modified to include form factors for the excitation of the octupole band as described in the text.

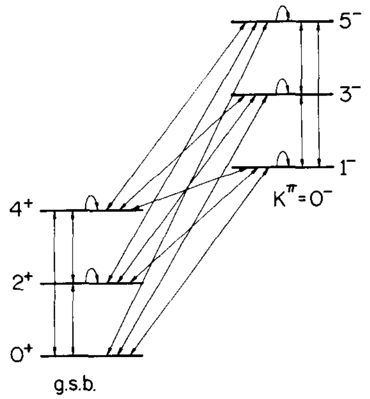

Fig. 3. Coupling scheme used in the CC calculations.

The results of DWBA calculations for the 1^- and 3^- states using form factor (1) and adjusting β_3 to fit the 3^- data are shown as solid curves in fig. 1. Although the DWBA curve for the 3^- state predicts stronger oscillations than observed experimentally the overall fit to the data is acceptable. The DWBA calculation fails to reproduce the data for the 1^- state both in shape (in particular the minima around 20° and 40°) and in magnitude. This is in contrast to the results of the excitation of the 1^- state of the $K^\pi = 0^-$ octupole band in ^{238}U via inelastic electron scattering [6] where a good fit both to the shape and magnitude of the 1^- data was obtained with the same β_3 used to fit the 3^- state of the same band.

The substantial underprediction of the DWBA curve to the strength of the 1^- state using form factor (1) with the octupole vibration coupling parameter determined from the excitation of the 3^- state indicates that an additional mode of excitation of this state is present. If only direct one-step excitations were possible, then we could obtain a reasonable fit to the 1^- data for $\theta \geqslant 50°$ in the DWBA framework by including the isoscalar dipole degree of freedom. The DWBA calculation including the coherent addition of both form factors (1) and (2) with $\beta_3 = 0.069$ and $\beta_1 = -0.0075$ is shown as dashed curve in fig. 1, which fits the magnitude of the 1^- data for $\theta_{lab} > 40°$ but deviates strongly from the data in the angular region between 20° and 40°. For the sake of comparison we have included in fig. 1 also the result of DWBA calculation using form factor (2) only with $\beta_1 = -0.0075$ (dotted curve). The shape of this curve does not reproduce that of the data either. In strongly deformed nuclei such as ^{152}Sm, however, strong couplings within one band, reorientation terms and two-step contributions can affect the calculated angular distributions of the octupole band states. Therefore CC calculations were performed using the program CHUCK and a search on β_3 was made which would lead to a good fit to the 3^- state. The most complete coupling scheme is shown in fig. 3. For the deformation parameters β_2 and β_4 of the $K^\pi = 0^-$ band we took the same values as for the gsb. The search resulted with $\beta_3 = 0.081$. The final calculations are shown in fig. 2. The fits to the 1^- and 3^- states are excellent. There is vast improvement if compared to the DWBA of fig. 1. This is also true for the 5^- state where the DWBA curve (not shown) fits the data badly. We would like to stress again that the fit to the 1^- state did not necessitate invoking the isoscalar dipole degree of freedom i.e. the addition of a direct term given by form factor (2). The addition of such a term with a small coupling parameter to the full CC scheme leads to a deterioration of the fit to the forward data points, as well as an overall overestimation of the differential cross section.

To conclude, the present CC analyses indicate that the isoscalar degree of freedom need not be invoked in describing the excitation of the octupole $K^\pi = 0^-$ band in ^{152}Sm. The same holds [8] for the $K^\pi = 0^-$ band in ^{156}Gd. This indicates that at least for this mass region the isoscalar dipole degree of freedom (p*-boson) does not play a role in the low-lying negative parity bands. This may not be the case for the mass region around Ra where the α-clustering states were suggested [7] to explain the low-lying negative parity bands.

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